MAKER: Applying 3D Printing to Model Rocketry to Enhance Learning in Undergraduate Engineering Design Projects

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Abstract

This paper presents several applications of 3D printing to model rocketry that were used to enhance experiential learning in two undergraduate engineering design courses. In a first-year seminar the students use a simplified systems engineering process to design and build model rockets to meet a mission goal defined by the faculty: determining their rocket's apogee using an onboard camera. The camera was mounted in a payload section that the students designed and 3D printed. The inclusion of 3D printing allowed the students to iterate on their designs and to quickly make changes. In addition, a senior-level advanced computer aided design course offered as a project option to students the complete design, analysis, build, and launch of fully 3D-printed model rockets. We report on student and faculty experiences and provide materials and suggestions for adoption in other programs.

Introduction

The "maker" culture (also referred to as a movement), which began in the early 2000s, has grown significantly and now represents an ever-expanding ecosystem of makers, suppliers, "Maker Faires", make spaces, etc. As STEM (science, technology, engineering, and math) educators, we should consider the maker movement as an important educational partner for providing more hands-on learning opportunities and enhanced student engagement in our courses and on our campuses. As Thomas Kalil of the White House Office of Science and Technology Policy said in a 2010 speech at the New York Hall of Science [1]: "After all, we wouldn't teach kids how to play football by lecturing to them about football for years and years before allowing them to play. And if education is about the 'lighting of a flame not the filling of a pail'—we should be putting the tools of discovery, invention and fabrication at the fingertips of every child—inside and outside of the classroom."

The maker culture typically emphasizes "informal, networked, peer-led, and shared learning motivated by fun and self-fulfillment." [2] It has grown up outside of formal learning structures, but many educational institutions are now actively seeking ways to adopt this culture because of its potential "to contribute to a more participatory approach to learning and create new pathways into topics that will make them more alive and relevant to learners…Maker culture emphasi[z]es the production of tangible artefacts that solve a need in their makers' everyday lives—and this explicitly includes playful or aesthetic 'needs'. It emphasi[z]es experimentation, innovation, and the testing of theory through practical, self-directed tasks." [2]

Model rocketry has been a favorite hobby of many budding engineers since the beginning of the space age following the launch of *Sputnik*. High-power rocketry (i.e., large model rockets), began in the mid-1980s with the availability of larger motors that were safe. Although predating the maker culture, model rocketry has been adopted within it wholeheartedly. The advent of 3D printing promises to make this connection even stronger.

Additive manufacturing—commonly referred to as 3D printing—is a rapidly growing field that has the promise to radically change the nature of advanced manufacturing. Its unique characteristics can enable the fabrication of designs not possible using traditional methods and also allows rapid design iterations. Additive manufacturing allows the fabrication of components directly from a digital design file using a layer-by-layer additive process. Each custom-printed model serves the unique needs of the person who designed it. Viewed as a new and exciting technology, students find 3D printing compelling, and many are now coming from high schools that have 3D printers and have been exposed to this technology already, so they expect it when they get to university.

Others have reported in the literature on the learning aspects of the maker culture [*cf.*, 3, 4], here we report on several activities we have developed for two courses at The Pennsylvania State University.

In a first-year seminar called "This *Is* Rocket Science", we introduce students to the space systems engineering process for rockets, balloons, and satellites. The students use a simplified version of this process to design and build model rockets to meet a mission goal defined by the faculty. In the Fall 2014 semester, the student teams were tasked with determining their rocket's apogee using an onboard camera. The camera was mounted in a payload section that the students designed and 3D printed. The inclusion of 3D printing allows the students to iterate on their designs and to quickly make changes.

A second course is a senior-level advanced computer aided design (CAD) course. Offered as a project option in this course, the elements of CAD, engineering analysis, integration of stock components, preparation of shop prints, fused deposition–based 3D printing, and model rocket science are packaged into a design contest. The students integrate CAD and related software-based analysis tools to report manufacturability, flight stability, drag, and design aesthetics. Safe designs are printed and flown as a class event. The contest winner is chosen based on a 900 point scoring rubric.

At the semester's end, both classes came together to launch their creations (Figure 1).

Figure 1: Two rockets await launch on their pads at the end of the semester. The black band on the large white rocket represents the location of the 3D-printed payload section and the red rocket is a fully 3D-printed rocket.

First-Year Seminar Course: "This *Is* Rocket Science"

There is strong evidence in the literature [*cf.*, 5, 6] that retention to graduation in higher education is improved by interventions and engagement in the first year. Such first-year interventions might take the form of a "low-stakes" course that includes close interaction between faculty and students, and/or connecting to student clubs and university research labs. The "This *Is* Rocket Science" first-year seminar (FYS) is designed to provide just such opportunities for engagement. Two faculty members, each with experience in space engineering and research, lead the class and work with the students during the semester. The teaching objectives for the class include:

1. Introduce first-year engineering students to atmospheric science and systems engineering;
2. Provide a comfortable setting for the student to begin his/her life as a Penn State student; and
3. (Perhaps most importantly) *have fun* while getting started on a career in engineering and, more specifically, space-related engineering.

Secondary goals for the course include:

1. Recruit students to the activities of the Student Space Programs Laboratory (SSPL) in the EE Dept. SSPL is a faculty-led, student-run lab in which students develop capabilities for space projects and fly space missions. SSPL has built payloads for balloon, rocket, and satellite platforms [7];
2. Provide training in the skills needed for the space-related work of the SSPL; and
3. Retain students in engineering, in general, and recruit them to electrical engineering, in particular.

To accomplish these goals, the students are asked, in teams, to build and launch two model rockets. As soon as the students walk in the door on the first day of class, they are assigned to teams and are given rocket kits to assemble as a team-building exercise. The rocket kits are familiar to most model rocketry enthusiasts, have full directions and cut-out parts for assembly, and use smaller motors (C-size and smaller). Typically, about a third of the class has some familiarity with this type of kit. These rockets are launched at the beginning of the second week at a social event that is sponsored and overseen by students from SSPL. This serves to engage the students with upperclassmen and introduces them to the design–build–launch–operate methods used in SSPL.

During the remainder of the semester, the teams are guided through a simple design–build–launch cycle on a much larger model rocket in response to a class "mission". While also provided in kit form, the rocket is a scale model of NASA's *Arcas* research rocket, which is 55 inches in length and requires a G-size motor. The kit requires much more effort to assemble as there are required modifications to accommodate the mission payload. Examples of mission statements from past years include:

- Measure and record the velocity, trajectory, position, or acceleration of a body moving through a ballistic trajectory; and
- Measure and record weather conditions at an altitude of approximately 1000 ft. For this payload, the class launched a "system of systems", with each team flying a sensor and contributing data to a distributed "weather station".

This past fall, the mission was:

- Determine the apogee of their rocket's flight using optical analysis of video/pictures from a camera mounted on a custom-designed, 3D-printed payload section.

Throughout the semester, the students are introduced to the elements of systems engineering and the design process. They learn about systems diagrams, "ConOps" (concept of operations), and the importance of specifying requirements for mission success. They are asked to write or present a preliminary design review, critical design review, and final report. Class lectures topics include:

1. How rockets work;
2. Phases of the project life cycle;
3. Layers of the Earth's atmosphere;
4. Systems engineering fundamentals;
5. Flow down from mission concept to measurable requirements; and
6. Topics specific to the mission concept.

Outside speakers—which have included astronauts, representatives from the space industry, and experts in system engineering and CAD modeling (i.e., SolidWorks)—provide a broad perspective on engineering for space and systems engineering.

About half the class periods were devoted to supervised work days. The students were provided with a baseline CAD model of the payload portion (see Figure 2). About a quarter of the students had some CAD experience (either from learning on their own or due to the fact that they were currently enrolled our first-year design course that teaches CAD). By providing the baseline model, we could avoid many of the issues of tight tolerances. As we found out, this did not limit the creativity at addressing the mission! Each team was provided a Mobius HD camera for integration. Their rockets with payloads were launched during the last week of classes.

Figure 2: CAD rendering of the baseline payload section that is modified by students, 3D printed, and integrated into the *Arcas* model rocket.

Feedback from the students, which will be factored into our next offering, is included in the Appendix. Response to the class has been positive. Student ratings of the class are high and SSPL can count on approximately a quarter of the course's student as high-quality recruits.

Senior-Level CAD Design Course

Proficiency in parametric design software is now an essential component of modern design and manufacturing. Additive manufacturing methods are applicable to and support the product development process in many industries. Product designs are collaborative and will include and use technology components beyond a manufacturer's primary knowledge base. Engineers need to communicate their designs across a company structure: executive, manufacturing, sales, and marketing.

The model rocket design contest is an educational delivery platform that allows for the inclusion of the challenges students are likely to experience as entry-level engineers. The pedagogy delivers the engineering challenge of designing, analyzing, building, and flying a model rocket produced on a 3D printer. The design software used was SolidWorks and the 3D printer used was the Makerbot 5th generation.

To enhance student engagement and provide a required design project, the project was presented as a "design contest" in which students would work in competition with each other. A succinct design challenge was developed for the contest so that students would have an immediate practical application of course lectures in parametric CAD. Students were provided a website (www.printedrockets.com) that includes all the information needed for the design contest:

1) Scoring rubric with phased goals and completion dates;
2) Model rocket design intent presented via an engineering shop drawing detailing: mandatory geometry, mass, and printer size (See Figure 3);
3) CAD assembly of the stock motor mount, which is provided as driving geometry for their assembly design; and
4) On-line recourse link that provides: NASA explanation of model rockets (theory), SolidWorks software download (design), Autodesk Flow Design (analysis), OpenRocket (model rocket design software for stability analysis), and Makerbot training videos.

After the rocket component parts were successfully designed and printed, a "Final Assembly Event" for experiential learning was held. During the event students confirmed the fit of their printed components with additional provided components needed for flight: motor mount, parachute, and shock cord. The two lower sections of the rocket were glued together and confirmation provided that the nose cone was able to be released by the ejection charge when in flight. Most rockets required additional mass (modeling clay was used) added to the nose cone for flight stability as predicted by OpenRocket.

Results

The design contest was an option in Fall 2014 with 10 of 40 students choosing to participate. All ten rockets attempted launch, five flew well and were recovered, three flew with noted instability, and two remained on the launch pad. Figure 4 provides renderings of all ten rockets and demonstrates the creativity and individuality of the students' designs.

A limited number of 3D printers and the 3D printing build time constrained the total number of rockets that could be produced in the time available. The printing time for each rocket ranged from 24–48 hours. Failed print jobs due to extruder jams also impacted the schedule. However, all ten participants was able to print their rockets and launch them (Figure 5).

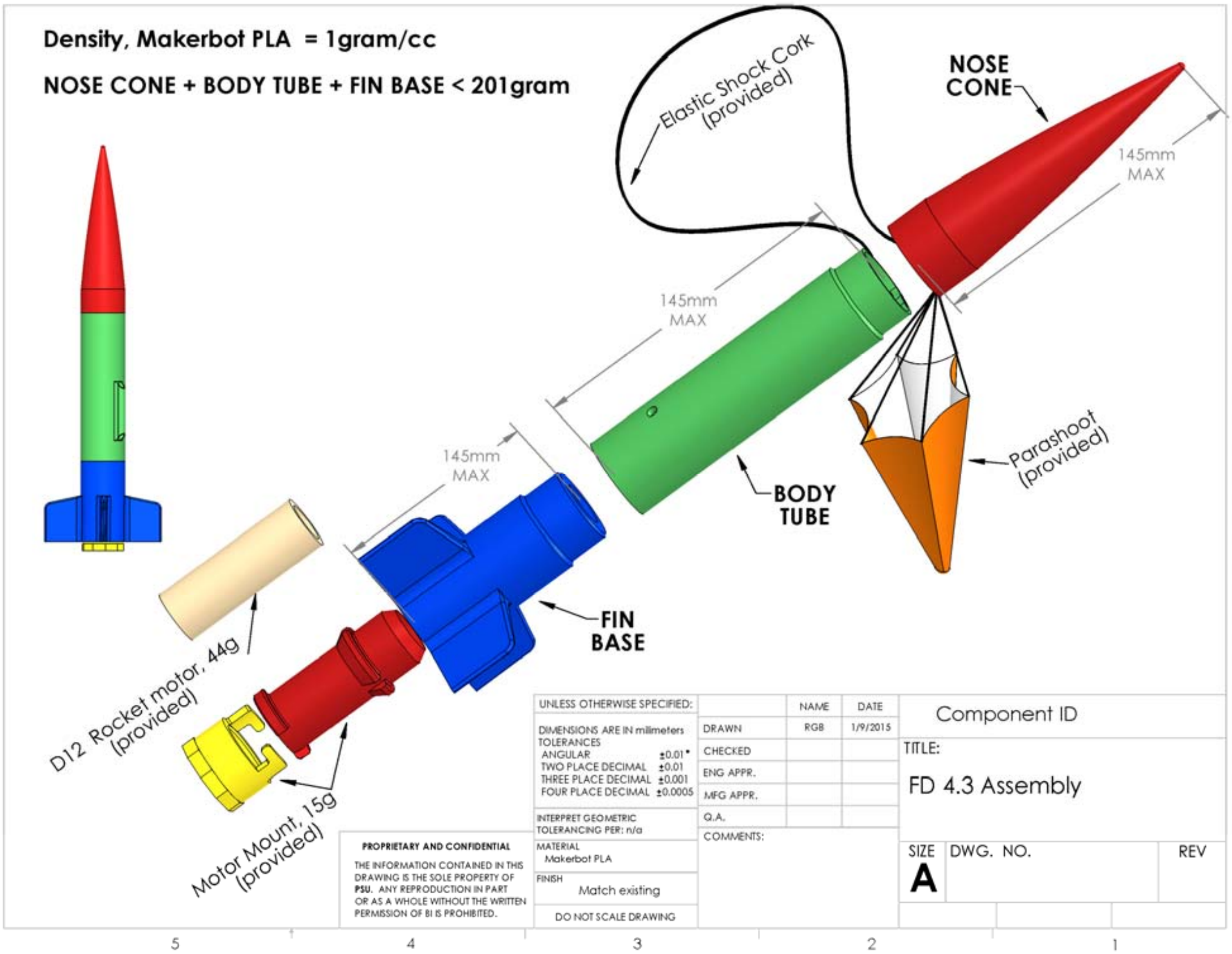

Figure 3: First page of design guidelines provided to students.

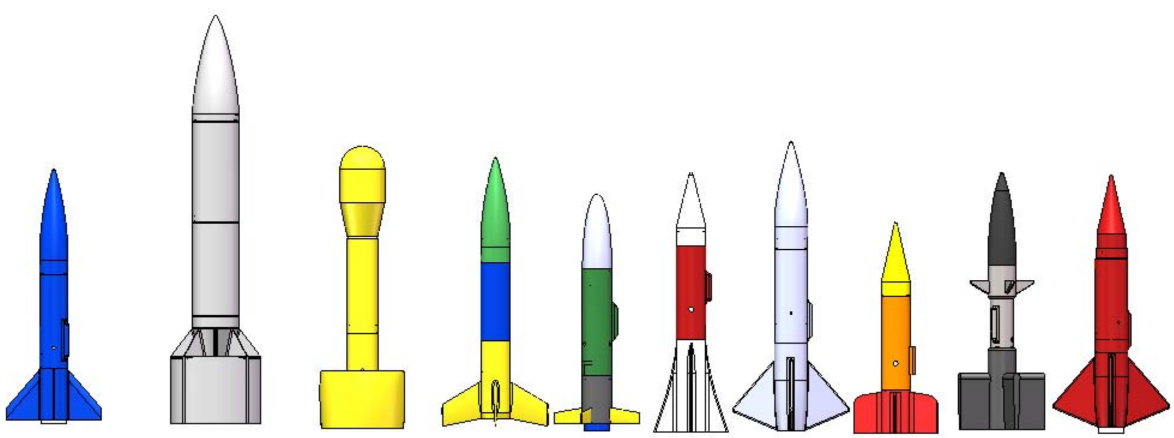

Figure 4: Rendering of the rockets designed, printed, and launched in the senior-level CAD design course.

(a) (b)

Figure 5: (a) Build environment, including 3D printer, for the model rockets; (b) printed rocket being launched.

Lessons Learned

There are several lessons learned that will be incorporated in the next offering of the design contest:

- Student engagement encouraged the expansion and refinement of the design contest.
- The availability of reliable 3D printers was critical to the success of the design contest. Students that did not participate directly in the design contest expressed interest in some other opportunity to be engaged in 3D printing. For planning purposes, four students per printer is a suggested ratio.
- The students learned that mass was the major factor in flight performance. Maximum mass will be added to the design intent.
- Students responded that the current simulation and analysis required is too much. We will consider reducing the analysis or allow students to work in teams of two such that the work load is divided.
- During the Final Assembly Event, students responded that they appreciated being able to physically realize a product of their own design; other students remarked that this was the first physical project they had ever produced.

Summary

This paper presents several innovative applications of 3D printing to model rocketry, which were used to enhance design and experiential learning in two undergraduate engineering design projects. The inclusion of 3D printing allows the students to iterate on their designs, see what works and does not, and to then make needed changes. 3D Printing is an important educational tool for providing hands-on learning opportunities for students and enhanced student engagement.

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Appendix: Student Feedback

FYS

Only one team of the five actually came up with a result for apogee: 792 ft. On the last day of class we held a mission review panel. The students contributed the following failure modes (reasons why they did not meet our requirements) and actions they might take in response:

- Rocket sections did not separate; parachute did not deploy
  - Figure out the gas pressure of the ejection charge and simulate it with air pressure to analyze why the sections are not separating
  - Grease the sliding sections instead of sanding them?
  - The payload they built may have added mass to the portion that had to eject. Put the parachute in the forward section and "eject" the lighter motor section?
- The camera did not run long enough (Payload sat too long on the launch rail)
  - Provide an easy way to turn the camera on when the rocket is on the rail
  - Create a countdown procedure that includes turning on the camera
  - Check to see if the rate of taking pictures is user-definable. Can fewer pictures be taken over a longer time?
- Camera broke upon impact
  - Build energy absorption into the payload section
  - Fill the payload section with padding/foam to cushion the impact
  - Coat the circuit board to protect the components.

So, this year's class has given us a starting point for next fall's rocket class. They have made their experience count by contributing their experience to the next group!

Senior CAD Design Course

The semester teaching evaluation produced the following comments relative to the design contest:

- "The final project (the design rocket) was very useful and fun way of applying what we had learned in the class."
- "A smaller design contest (i.e., maybe not have to do the flow sim?) it was a lot of work. It was doable, but it was much more than what would have been done for the standard project."
- "I would possibly do more 3D printing projects if possible. Those really drove home SolidWorks techniques and required a lot of thinking from a design standpoint. Maybe segment one large project into several small ones. Avoid last-minute work."
- "Rocket Project. This is one of the best classes I have ever taken. Class size is just about right. Professor is cool as well."
- "Very good structure of the course—labs and quizzes help a lot. The rocket project was fun as well. Having food at the outside class was great as well!"
- "Doing something that everyone can 3D print for a lab one week—it would be cool to take away something physical from this class!"